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INTERNATIONAL ELECTROTECHNICAL COMMISSION

HIGH-VOLTAGE TEST TECHNIQUES

Part 4: Application guide for measuring devices

FOREWORD

1) The formal decisions or agreements of the IEC on technical matters, prepared by Technical Committees on which all the National Committees having a special interest therein are represented, express, as nearly as possible, an international consensus of opinion on the subjects dealt with.

2) They have the form of recommendations for international use and they are accepted by the National Committees in that sense.

3) In order to promote international unification, the IEC expresses the wish that all National Committees should adopt the text of the IEC recommendation for their national rules in so far as national conditions will permit. Any divergence between the IEC recommendation and the corresponding national rules should, as far as possible, be clearly indicated in the latter.

PREFACE

This standard has been prepared by IEC Technical Committee No. 42, High-Voltage Testing Techniques.

It constitutes a revision of that part of IEC Publication 60 which deals with measuring and calibration procedures which will satisfy the specified requirements for accuracy. More specifically it replaces Section eight, the appendices and the technical notes of the IEC Publication 60.

During a meeting in Bucharest in 1962, a general discussion was held concerning which modifications and addenda were foreseen for IEC Publication 60, then being printed. Subsequent drafts were circulated and discussed in Aix-les-Bains in 1964, in Tokyo in 1965, in London in 1968, in Leningrad in 1971 and in Ottawa in 1975. As a result of this latter meeting, a draft, Document 42(Central Office)27, was submitted to the National Committees for approval under the Six Months' Rule in April 1976.

The following countries voted explicitly in favour of publication:

Austria	Norway
Belgium	Poland
Brazil	Romania
Canada	Spain
Czechoslovakia	Sweden
Denmark	Switzerland
Egypt	Turkey
France	Union of Soviet
Germany	Socialist Republics
Italy	United Kingdom
Japan	United States of America
Korea (Republic of)	Yugoslavia

Other IEC publications quoted in this standard:

Publications Nos. 52: Recommendations for Voltage Measurement by Means of Sphere-gaps (One Sphere Earthed).

60-2: High-voltage Test Techniques, Part 2: Test Procedures.
60-3: High-voltage Test Techniques, Part 3: Measuring Devices.
186: Voltage Transformers.

HIGH-VOLTAGE TEST TECHNIQUES

Part 4: Application guide for measuring devices

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SECTION ONE – GENERAL

1. Scope

This application guide is applicable to:
— measurement of direct voltages;
— measurement of alternating voltages;
— measurement of impulse voltages;
— measurement of impulse currents;
— measuring errors.

2. Object

The object of this application guide is to provide information on:
— measuring devices for direct voltages;
— measuring devices for alternating voltages;
— measuring devices for impulse voltages;
— measuring devices for impulse currents;
— statistical evaluation of measuring errors.

In general, use of the devices and of the measuring and calibration procedures described herein will satisfy the requirements of accuracy specified in IEC Publication 60-3, High-voltage Test Techniques, part 3: Measuring Devices. Their use is not mandatory: others may be used if they are shown to have equal accuracy. Voltage measurements with sphere-gaps are dealt with in IEC Publication 52, Recommendations for Voltage Measurement by Means of Sphere-gaps (One Sphere Earthed).

SECTION TWO – MEASUREMENT OF DIRECT VOLTAGES

3. General

Systems for measuring direct voltages generally consist of a measuring instrument and a high impedance across which almost the entire test voltage will appear. The value of the impedance is made high to minimize the power consumption of the measuring system. Some of the more commonly used systems for measuring the steady-state and ripple values are described below.

4. **Systems for measuring the steady-state value of direct voltages**

a) *Instrument used with series resistor*

A direct current measuring instrument is connected in series with a stable high ohmic value resistor.

b) *Instrument used with voltage divider*

A voltmeter is connected across the low voltage arm of a resistance voltage divider. The resistance of the voltmeter must be taken into account when determining the ratio of the divider.

Note. – Depending on the type of instrument used, these methods will determine the arithmetic mean, the r.m.s. or the peak value of the voltage.

c) *Electrostatic voltmeter*

An electrostatic voltmeter has two electrodes which are connected to the points between which the high voltage is to be measured. The electrostatic field between the electrodes generates an attracting force which is proportional to the r.m.s. value of the voltage. By measurement of this force, an indication of the r.m.s. value of the high voltage can be derived. This measuring principle can be used over the range of frequencies from zero up to several megahertz. If the measuring system is not shielded, special attention should be given to errors caused by stray fields and space charges.

d) *Generating voltmeter*

A generating voltmeter is a capacitive device the input terminals of which are connected to the points between which the voltage is to be measured. It is essentially a variable capacitor, the capacitance being cyclically changed between two fixed values. A measuring instrument together with a suitable switching or rectifying device measures the change of charge which, in general, is proportional to the mean value of the direct voltage. By a suitable choice of frequency of the capacitance variation and its phase angle relative to the voltage to be measured, the peak value or any intermediate value can be determined.

5. **Systems for measuring ripple voltage**

a) *Oscilloscope used with voltage divider*

An oscilloscope is connected to the low voltage arm of a voltage divider having a suitable frequency response. It should be noted that the capacitance of the cable between the divider and the instrument can modify the frequency response.

b) *Instrument used with filter*

Such a device consists in general of an instrument connected to the circuit in such a way that the d.c. component is filtered out. A typical arrangement consists of a high voltage capacitor in series with a resistor across which a voltage measuring instrument is connected.

c) *Instrument measuring the rectified current through a capacitor*

A capacitor in series with a full-wave rectifier is connected to the points between which the voltage is to be measured. The ripple amplitude U_r is related to the rectified mean current I_r flowing through the capacitor by:

$$U_r = \frac{I_r}{4\,C\,f}$$

where:
C = capacitance of the capacitor
f = fundamental frequency of the ripple

If the ammeter measuring the capacitor current is connected so that only alternate half-cycles of current are measured, the factor 4 in the above expression becomes 2.

The method is of limited application. If the ripple has more than one peak during each half-cycle, then the accuracy depends upon the type of rectifier which is used.

6. Determination of voltage ratios and scale factors

a) Instrument used with series resistor

The resistance of the series resistor is generally determined by a low voltage bridge measurement using direct voltage. From this value and the characteristics of the instrument. the scale factor is deduced.

The scale factor can also be determined by comparison during parallel operation with an approved direct voltage measuring system.

The voltage and temperature stability of the series resistor at high voltage can be verified by subjecting individual components of the resistor to suitable tests over the range of voltages and temperatures at which they will operate.

b) Instrument used with voltage divider

Methods for determining the ratio of voltage dividers are discussed in Clause 17.

c) Electrostatic voltmeter and generating voltmeter

Measuring systems of these types can be calibrated by comparison during parallel operation with other approved measuring systems.

Note. – During reactions between proton or deuteron beams with different light nucleus elements, precisely known resonant energies exist for which the cross-section for a reaction is a maximum. This effect can be used as a very accurate absolute calibration method for high d.c. voltage measuring systems.

7. Determination of the amplitude-frequency response of a measuring system

To determine the amplitude-frequency response of a measuring system, a sinusoidal voltage is applied between its input terminals. The ratio of the output to the input amplitudes is recorded as a function of frequency. The range of frequencies should extend from a low value to at least the highest of importance present in the voltage to be measured. The measurements are usually made at a low value of input voltage.

8. Possible sources of error and precautions

When using direct voltage measuring systems of very high resistance, care must be exercised to avoid errors due to corona effects, or to leakage currents across insulating surfaces which may be contaminated by pollution or condensed moisture. Suitably dimensioned high voltage electrodes, guard circuits and surface treatment minimize such errors and thus the requirements for current level can be reduced.

Errors can also be caused by resistors which have significant voltage or temperature coefficients and by instruments which are subject to drift.

Generating and electrostatic voltmeters may develop errors due to field distortion arising from electrostatic charges on the surface of insulating materials or in space.

Overstressing of components in measuring equipment upon flashover of a test object or measuring errors due to partial discharges can occur in a measuring system having a high frequency response appreciably in excess of its response in the low frequency range. These phenomena are usually associated with the presence of stray inductance.

SECTION THREE – MEASUREMENT OF ALTERNATING VOLTAGES

9. General

Systems for measuring alternating voltages generally consist of a measuring instrument and a voltage transformer, voltage divider, or a high impedance across which almost the entire test voltage will appear. The devices usually have high impedance to keep the loading of the test circuit within acceptable limits. Some of the more commonly used systems for measuring high alternating voltages and the amplitudes of harmonics are described.

10. Systems for measuring the amplitude of alternating voltages

The following systems will in most cases measure the peak or the r.m.s. value of an alternating voltage or the mean value of a rectified alternating voltage according to the type of instrument and arrangement used. Measurement of the rectified capacitance current (method c)) will determine the peak-to-peak amplitude, and the electrostatic voltmeter (method d)) measures the r.m.s. value.

a) Instrument used with voltage transformer
A voltmeter is connected across the low voltage winding of a voltage transformer of either the inductive or capacitive type. In general, the choice of the instrument is not restricted by its input impedance.

b) Instrument used with voltage divider
A voltmeter or an oscilloscope is connected across the low voltage arm of the divider through a measuring cable. In general, the input impedance of the low voltage measuring circuit including the measuring cable affects the divider ratio. In most cases, a capacitive voltage divider together with a low voltage circuit measuring the peak value of the high voltage is used.

c) Capacitor used with a rectifying device
A capacitor in series with a full-wave rectifier is connected to the points between which the voltage is to be measured. The peak value of the voltage U_p is related to the rectified mean current I_r flowing through the capacitor by

$$U_p = \frac{I_r}{4\,Cf}$$

where:
C = capacitance of the capacitor
f = frequency of the alternating voltage

If the ammeter measuring the capacitor current is connected so that only alternate half-cycles of current are measured, the factor 4 in the above expression becomes 2.

The method is of limited application. If the waveform has more than one peak during each half-cycle, then the accuracy depends upon the type of rectifier which is used.

d) Electrostatic voltmeter

This device is described in Item *c)* of Clause 4 for use with direct voltages. It can also be used for measuring the r.m.s. value of alternating voltages in a large range of frequencies up to several megahertz.

e) Generating voltmeter

A generating voltmeter is described in Item *d)* of Clause 4 for use with direct voltages. Such a voltmeter may also be used for the measurement of alternating voltages. By a suitable choice of frequency of the capacitance variation and its phase angle relative to the voltage to be measured the peak value or any intermediate value can be determined.

f) Instrument used with series resistance

An alternating current measuring instrument is connected in series with a stable high ohmic value resistor.

11. Systems for measuring the amplitude of harmonics

a) Oscilloscope used with voltage divider

An oscilloscope is connected across the low voltage arm of a capacitor voltage divider. This method is sufficient only if the accuracies of both the recording and the subsequent analysis are sufficient to ensure that the requirements are met. The method has limited accuracy especially in the case of low amplitude harmonics.

b) Instrument used with filter

A filter is used to suppress the fundamental component of the voltage and the r.m.s. value of the residual harmonics is measured with an appropriate instrument. Alternatively, but with less accuracy, the peak value of the combined harmonics may be measured.

c) Wave analyser used with voltage divider

This system permits separate measurement of the r.m.s. value of the fundamental and each harmonic.

12. Determination of voltage ratios and scale factors

a) Instrument used with voltage transformer

Methods for determining the ratio of voltage transformers are covered in IEC Publication 186, Voltage Transformers.

b) Instrument used with voltage dividers

Methods for determining the ratio of voltage dividers are described in Clause 17.

c) Electrostatic voltmeter and generating voltmeter

Measuring systems of these types can be calibrated by comparison during parallel operation with other approved measuring systems.

d) Instrument used with series resistance

Methods for calibrating systems of this type are described in Item *a)* of Clause 6. However, the impedance of this resistor and the scale factor should be determined within the frequency range of the alternating voltages to be measured.

13. Determination of the amplitude-frequency response of a measuring system

To determine the amplitude-frequency response of a measuring system, a sinusoidal voltage is applied between its input terminals. The ratio of the output to the input amplitudes is recorded as a function of frequency. The range of frequencies should extend from a low value to at least the highest of importance present in the voltage to be measured. The measurements are usually made at a low value of low input voltage.

14. Possible sources of errors and precautions

Due to the high impedances of some voltage dividers and series impedance elements, the effects of corona and stray capacitances may result in serious errors. Such errors can often be minimized by the use of suitably dimensioned high-voltage electrodes and guard circuits. To avoid such effects on capacitor dividers, it is recommended that, when the capacitor is not effectively shielded, the total series capacitance in picofarads be at least 30 to 40 times its overall length in metres.

Errors may also be caused by resistors which have significant voltage or temperature coefficients and by instruments which are subject to drift.

Electrostatic and generating voltmeters may develop errors due to field distortion arising from electrostatic charges on the surfaces of insulating materials or in space.

When a high-voltage series capacitor is used for voltage measurement, special protection of the measuring instruments is necessary during disruptive discharge tests. Disruptive discharge of a test object connected in parallel with measuring systems of this type results in the application of fast rising current surges to the rectifiers and instruments, which should be suitably protected.

Overstressing of components in measuring equipment upon disruptive discharge of a test object, or measuring errors due to partial discharges, can occur in a measuring system having a high-frequency response appreciably in excess of its response in the low-frequency range. These phenomena are usually associated with the presence of stray inductances.

SECTION FOUR – MEASUREMENT OF IMPULSE VOLTAGES

15. General

Measuring systems for lightning and switching impulse voltages must be capable of recording much higher rates of change of voltage than those used for measuring other types of high voltage. Consequently, the components of the system should be specifically designed to have a good transient response. Therefore, a large portion of this section deals with methods for determining the response characteristics of measuring systems and the errors introduced by an inadequate response. A circuit used for checking the response characteristic of a measuring system is shown in Figure 1, page 66. Other circuits are also applicable.

It is also important that the measuring system does not load the generating system so heavily that it is prevented from developing the required high rates of change of voltage across the test object.

The induced voltages from heavy currents, or voltages outside of the measuring system, are not taken into account when considering the response and the measuring errors. Special care should be taken when the result of response measurements are applied to tests with heavy currents.

It should be realized that the voltage across the test object is rarely identical in all respects to that across the voltage divider.

16. Measuring system components

Most high-voltage impulse measuring systems (except sphere-gaps) consist of a voltage divider, an oscilloscope or an indicating instrument or both, high-voltage leads, low-voltage measuring cables and earth return circuits. A high-voltage damping resistor may also be included. Important features of these components are explained in the following sub-clauses.

16.1 Voltage divider

Most high-voltage dividers have distributed stray capacitances to earth and to neighbouring earthed or live objects. In resistor dividers, these capacitances affect the response characteristics since they must be charged and discharged through the divider resistance; in capacitor dividers. the stray capacitances affect the scale factor of the system.

The effect of stray capacitance can be reduced in resistor dividers by keeping the resistance as low as possible without unduly loading the generating system and by using shielding electrodes at the high-voltage end of the divider. These electrodes provide a capacitive path for charging the stray capacitance to earth.

In capacitor dividers, the capacitance of the divider should be large enough to minimize the effect of stray capacitance. Capacitor dividers for rapidly changing impulses may have large overshoots or oscillations in their output due to parasitic inductances in the low-voltage arm.

Mixed dividers consist of both capacitive and resistive elements. In such dividers, the effect of stray capacitance depends on the manner in which the component parts are connected.

16.2 High-voltage lead

The length, position and diameter of the lead connecting the high-voltage terminal of the voltage divider to the high-voltage terminal of the test object may all influence the performance of the measuring system. For any particular measurement, the length of the lead should be stated and it should be within the range of lengths for which the measuring system was calibrated. When important. its position should be approximately the same for a test as during calibration.

Ideally, the diameter of the lead should be large enough to prevent corona since corona on the lead can affect the performance of the measuring system. When corona cannot be prevented. it is better to use a small diameter lead. Vigorous discharges in the vicinity of the divider should be avoided.

The high-voltage lead should normally be connected directly to the high-voltage terminal of the test object and not to the impulse generator or any point on the interconnecting lead. This avoids inclusion in the measurement of the inductive voltage drop in this lead. However. when measuring full standard lightning impulses or impulses chopped on the tail. it can in general be

assumed that the error due to connecting the divider to an intermediate point on the lead between the generator and test object is negligible if the condition $\sqrt{LC} \leqslant 0.05$ µs is fulfilled. In this relationship, L is the inductance in microhenrys of that part of the lead which is between the divider and the test object (roughly 1 µH/m) and C is the effective capacitance of the test object in microfarads. The total length of lead between the voltage divider and the test object is then considered to be the high-voltage lead of the measuring system.

16.3 *Damping resistor*

A resistor of very low inductance may be inserted in the high-voltage lead to damp oscillations. This resistor may either be located close to the divider or at the input end of the high-voltage lead. In the first case the resistor is considered to be a part of the divider and the system is then described as a two-component system. In the second case the system is described as a three-component system.

Whatever the position of the resistor, its value must be taken into account when determining the ratio of the system.

The resistor may have an appreciable influence on the response of the measuring system. Only two-component systems are dealt with in this application guide.

16.4 *Oscilloscope*

An impulse oscilloscope is essentially a well screened instrument with a high-writing speed and with a single sweep time base which can be triggered in synchronism with the impulse. The high-voltage supplies of the instrument should be stabilized and have practically no ripple. Means of calibrating the sweep speed and the voltage deflection sensitivity should be provided. Provision should also be made for photographic recording of the oscillograms.

It is important that the deflection plates of the oscilloscope remain under the same conditions of earthing and biasing during the calibration and during the recording of the impulse voltages. Impulse oscilloscopes are not normally equipped with amplifiers and the leads to the deflection plates are kept as short as possible to obtain good high-frequency performance. Oscilloscopes with amplifiers are quite acceptable if they have a sufficiently fast response and their voltage measuring accuracy is sufficiently high. However, such instruments are especially sensitive to disturbances.

The oscilloscope is normally provided with an input connector for the coaxial cable from the voltage divider. The input impedance as measured at this connector should either match the characteristic impedance of the coaxial cable or be as high as possible depending on the type of the divider (see Sub-clause 16.6). Sometimes, both possibilities are provided for. In either case, the input capacitance of the oscilloscope should be kept to a minimum. The instrument may also include an internal attenuator to provide a stepwise division of voltage between the input connector and the deflection plates.

16.5 *Peak voltmeter*

The peak voltmeter is an instrument which usually functions by charging a capacitor through rectifiers, to a voltage which is proportional to the peak value of the impulse to be measured. The charge is retained on the capacitor and is read by means of a very high-impedance amplifier plus a recording or indicating instrument which is incorporated into the device. Such a device has an error which depends on the shape of the impulse to be measured and should be determined experimentally. The input impedance of the instrument is subject to the same restrictions

as noted for the oscilloscope. It should be noted that most instruments of this type have been found to be very subject to interference, especially when measuring inpulses which are sharply chopped.

Note. – It is important to check the overall scale factor, the stability, the response characteristics and the sensitivity to disturbances both for impulse oscilloscopes and peak voltmeters. Methods for this checking are under consideration.

16.6 *Coaxial cable and matching devices*

Any measuring cable on the low voltage side of a measuring system should be coaxial and of the high-frequency type. The dielectric loss of the insulation and the resistance of the inner conductor of the cable and that of the sheath may introduce errors. It is essential that the cables be matched at one or both ends to prevent multiple reflections which might result in measurement errors.

If the cable is connected to two or more instruments at the same time and the length of the additional connecting cables is not negligible with respect to that of the main cable, a matching device should be inserted and all cables matched. When the lengths of the additional cables are negligible no matching devices are used and only one cable is matched.

With resistor dividers, the cable is normally matched at the instrument end and sometimes at both ends (see Figure 2a, page 66). Any attenuator or connecting device inserted in the cable should match the cable impedance. When capacitor dividers are used, the cable is usually matched only at the divider end by connecting the matching impedance in series with the cable (see Figure 2b, page 66). Any attenuator or connecting device inserted in the cable should have an input impedance as high as possible. Other methods of matching may be used provided that the response of the system meets the requirements specified in Clause 23.

16.7 *Earth returns*

There are normally several points in the impulse generating and measuring systems which are interconnected and connected to the earth terminal of the test object. It is important that the impedance between all of these points be kept to a minimum. Special care is necessary in areas of heavy earth currents, that is at the earth terminals of the test object, of the impulse generator, and of any front capacitor. This reduction of impedance may be accomplished by the use of earth return conductors consisting of large non-magnetic metal sheets or by making short earth connections to a large metal sheet or mesh in or on the floor of the test area.

17. Determination of voltage divider ratios and scale factors

The scale factor of a measuring system is usually obtained by multiplying the voltage ratio of the dividers by the sensitivity of the instrument. This sensitivity is determined by conventional methods.

Various methods are available for the determination of the ratio:

a) By calculation of the ratio based on the measurement of the impedance of the individual components.

b) By simultaneous measurements of the input and output voltages of the divider.

c) By the use of some form of bridge circuit in which the output of the divider is balanced against the output of an accurate adjustable divider. (This method is usually more accurate than the two former methods.)

The voltage ratio of a divider is usually determined at low voltage. For dividers of the resistor type, measurements can be made according to *b)* or *c)* with either alternating or direct voltage. For capacitor dividers alternating voltages are used. To check that the determined ratio is applicable within a given frequency range, it is recommended that the ratio be determined at several frequencies, for example power frequency and 1 kHz.

In addition to the determination of the ratio it is normally necessary to check that the voltage ratio is constant within ± 1 % for the region of times to peak for which the divider is intended to be used, and does not change more than 5 % for the longest time to half value to be considered. This check should be done by means of the step response or by comparison with an approved measuring system during the application of the appropriate impulse shapes.

With dividers of the capacitor or mixed type, it is generally necessary to check the scale factor of the system in the actual test arrangement to verify the voltage ratio when this ratio has been determined independently. This is because the presence of stray capacitances can affect the voltage ratio and moreover, the ratio measured with a low frequency alternating voltage may differ from that applicable when measuring impulse voltages.

A suitable method for checking the scale factor is to make simultaneous measurements using two systems – the system to be checked and one involving either a suitable resistor divider or some other approved measuring system. In the check, an impulse voltage of the type to be measured should be used. The test may be done at a voltage level well below the rated voltage of the system being checked, thus a resistor divider or approved measuring system of relatively low voltage rating may be used. However, it should be recognized that the voltage ratio determined at low voltage may differ from that applicable at high voltage if there are voltage-dependent effects in the measuring system, as for example, corona.

18. Response of a measuring system

The accuracy of an impulse measurement can best be evaluated by using some form of generalized response of the measuring system. The type of response which has been selected for impulse measuring systems is the unit step response.

In principle, the step response of an impulse voltage measuring system is the oscillogram obtained when a step voltage is applied between the two input terminals. In practice, the system is modified and an approximate step response called the "experimental unit step response" is obtained.

This response can be used to obtain certain parameters of the true response which are useful for determining the accuracy of a measurement. These parameters are listed below together with an indication of their applicability. Their determination from experimental step response oscillograms is described in Clause 20. They can also be obtained with the use of a sphere-gap as described in Clause 21.

Response parameters

Parameters	*Application*
Response time: T (Sub-clause 20.2)	Determination of errors in measurements of front chopped impulses, corrections
Partial response time: T_α or T'_α (Sub-clause 20.6)	Correction of measurement of superimposed oscillations
Lead response time: T_ℓ (Sub-clause 20.4)	Used to determine T when length of H.V. lead is changed. (T_ℓ is a component of T)
Response time of system without H.V. lead: T_t (Sub-clause 20.4)	Quality parameter of divider to be supplied by manufacturer
Experimental response time: T_n (Sub-clause 20.2)	Used for the determination of T
Initial distortion time: T_o (Sub-clause 20.3)	Measurement of time parameters and amplitude of front chopped impulses
Resonant frequency range: f_r (Sub-clause 20.5)	Measurement of superimposed oscillations
Virtual zero: $0'$ (Sub-clause 20.1)	Considered to be the starting point of the step, of the response and also of the signal to be measured

19. Experimental procedure for measuring the unit step response

From the high-voltage input terminal of the measuring system, a conductor of the same diameter as the high-voltage lead of the measuring system is arranged to run vertically downward to a small step generator located at ground, as illustrated in Figure 1, page 66. The step generator must have essentially zero impedance while generating the step and during the subsequent response, and is some form of high-speed switch which short-circuits the two input terminals. The voltage step is generated by applying a voltage across the switch and then closing the switch. Suitable switches for the purpose are a mercury-wetted relay, or a small gap having an essentially uniform field (of about 1 mm spacing) which is caused to spark over. Large gaps are not satisfactory for an accurate determination because they do not have a sufficiently fast rate of change of voltage nor do they have a sufficiently low impedance after sparkover.

If a mercury-wetted relay is used, the voltage source can be a low direct voltage source connected through a current limiting resistor. The output from the voltage divider will generally be too low to record with the normal impulse oscilloscope and an oscilloscope having a higher sensitivity will have to be used. This oscilloscope should have response characteristics similar to those of the impulse oscilloscope normally used, as otherwise erroneous information will be obtained about the behaviour of the measuring system when measuring rapid rates of change of voltage. It is also important that the normal impedance to earth from the divider output and the normal cabling arrangements be maintained when using this oscilloscope, especially when taking the response of capacitive dividers.

If a gap having an essentially uniform field is used as the switch, an impulse having a front of 10–15 µs can be applied, the amplitude being adjusted to cause the gap to spark over at or near

the peak of the voltage. For capacitor dividers, direct or alternating voltages may be used. The sparkover voltage of the gap can be increased by increasing the pressure; this may eliminate the need for amplification and thus permit the use of the normal impulse oscilloscope.

It is recommended that the experimental procedure be carried out for several lengths of the high-voltage lead covering the range which is likely to be used in practice.

It is also recommended that the response oscillograms be made with several sweep speeds (see Sub-clause 20.1).

20. Determination of the response parameters from step response oscillograms

Typical response oscillograms obtained by the unit step method are shown in Figure 3, page 67. In many, the initial part is either rounded as in Figure 3c or shows bumps, or oscillations as in Figures 3f to 3h. This initial region is referred to as the 'toe' region and its shape is important when analysing front-chopped oscillograms.

In order to establish the response parameters, a virtual zero point 0′ has to be determined; a procedure for doing this is given in Sub-clause 20.1. This virtual zero 0′ is considered to be the starting point of the step, the response, and also of the signal to be measured in a practical test.

20.1 Determination of the virtual starting point 0′ and unit amplitude

The virtual starting point 0′ of a step response oscillogram is defined as the intersection of the time axis and a straight line drawn as a tangent to the steepest portion of the front of the response.

In the case of a response with oscillations on the front, a mean curve is drawn through the oscillations and used to determine the straight line. In the case of significant initial distortion as shown in Figures 3f, 3g and 3h, this distorted part is neglected when drawing the tangent and the virtual zero point is determined as above. It is self-evident that the determination of 0′ is to a certain extent arbitrary, particularly in the case of responses having large initial distortion. The level corresponding to unit amplitude must also be determined. In IEC Publication 60-3, this amplitude is defined with the help of the scale factor of the system (see Sub-clause 25.1). A simple but sufficiently accurate method for the determination is to take the level to which the response approaches or around which the response oscillates as unit amplitude. This may require the use of different sweep speeds. To clearly determine this reference line it may be desirable to eliminate oscillation in the step response. This can be done with capacitor dividers by inserting a resistor at the junction of the measuring system lead and the switch used for generating the step.

20.2 Determination of the response time T

To determine the response time T, the areas T_a, T_β, etc. are determined as the areas enclosed between the step and unit step response, both of which are assumed to start at 0′. In the case where there is an initial deviation between the response oscillogram and the straight line used to determine 0′, such as shown in Figures 3c to 3h, this initial deviation is neglected and the straight line is considered to represent the response for that part.

In the experimental circuit for determining the response parameters, a vertical lead has to be used to connect the horizontal divider lead to the step generator. An approximate step response T_n called the "experimental unit step response" is obtained and equals:

$$T_n = T_a - T_\beta + T_\gamma - \ldots$$

The response time T is determined from T_n by correcting for the effect of the vertical lead. The response time T is given by:

$$T = T_n + \tau_v \left(1 - \frac{Z}{R}\right)$$ Equation 20a

where:

τ_v = propagation time along the vertical lead: $\tau_v = h/c$ where h is the length of the vertical lead and c is the velocity of propagation of an electromagnetic wave (300 m/μs)

R = resistance between the top of the divider and ground. R is infinite for capacitor dividers and for mixed dividers with series resistance

Z = characteristic impedance of the vertical lead. For practical purposes, it is sufficiently accurate to use the impedance of the horizontal lead at a height above ground equal to the length of the vertical lead, given by:

$$Z = \frac{1}{2\pi} \sqrt{\frac{\mu_0}{\varepsilon_0}} \cdot \ln \frac{4h}{d} \approx 60 \ln \frac{4h}{d} \; \Omega$$

where:

d = diameter of the lead
μ_0 = permeability of vacuum = $4\pi \times 10^{-7}$ H/m
ε_0 = permittivity of vacuum = 8.85×10^{-12} F/m

The term $\tau_v \left(1 - \frac{Z}{R}\right)$ represents the correction for the effect of the vertical lead.

20.3 *Determination of the initial distortion time T_0*

The initial distortion time T_0 ist defined as the area between the unit step response and the straight line used to determine 0', and is taken from the moment the response first deviates from zero up to the moment when it meets the straight line (see figures 3*f*, 3*g* and 3*h*).

20.4 *Determination of the response time T_t of the system without high-voltage lead*

The response time T_t of the system without high-voltage lead is determined from:

$$T_t = T + \tau_\ell \left(1 - \frac{Z}{R}\right)$$

$$= T + T_\ell$$ Equation 20b

$$\tau_\ell = \ell/c$$ Equation 20c

where:

τ_ℓ = propagation time along the horizontal lead
ℓ = length of the horizontal lead
T_ℓ = lead response time (for the significance of the other symbols, see Sub-clause 20.2)

Note. – In Appendix A, a method is given for estimating a value for T_t for a simple resistor divider.

20.5 Determination of the resonant frequency range

The resonant frequency range is defined as the range extending from the resonant frequency visible on the step response taken with the longest practicable lead to about 1.5 times the frequency which is visible when the shortest lead is used. Oscillations on the front of the response oscillogram as shown in Figure 3e, page 67, are neglected in this determination.

Note. – When determining the resonant frequency range, it may be found desirable to take an additional step response with all series damping resistors in the divider short-circuited in order to increase the amplitude and duration of the oscillations. ·

20.6 Determination of partial response time T_a

The partial response time T_a is given by the area between the unit step shifted to the point 0′ and the unit step response curve up to the instant when the response first reaches unit amplitude (see Figure 3).

This is the quantity which is related to the effective steepness of the step response and is indicative of the ability of the measuring system to reproduce oscillations superimposed on an impulse voltage. In particular cases, a different parameter T_a' is used (see Sub-clause 23.2 and Figure 8, page 71).

21. Determination of the response parameters by the sphere-gap method

The sphere-gap to be used in this method is a vertical one having 250 mm diameter spheres. It must meet the requirements laid down in IEC Publication 52 and shall be adequately irradiated. The sphere-gap is used in two different ways for the determination of the step response parameters. For the determination of T and T_t, the voltage/time characteristic of the gap is used, whereas for determining T_a, the gap is used as a step generator. Note₀ however, that using the gap as a step generator is not satisfactory for determining T and T_t because the gap sparkover is too slow.

21.1 Determination of the response time T

The above sphere-gap, when set to a spacing of 60 mm, has an accurately known voltage/time curve for linearly rising voltages of negative polarity. The curve is reproduced in Figure 4, page 68, in a form which enables it to be used for determining the response time T of a measuring system.

To determine the response time, the measuring system is used to measure one or more points on the curve of Figure 4. The difference between the value given by the curve and the measured value of sparkover voltage, corrected to standard atmospheric conditions (see IEC Publication 52) is inserted in the following formula to obtain the response time of the system.

$$T = \frac{\Delta U}{S} \text{ (ns)} \qquad\qquad \text{Equation 21a}$$

where:

ΔU = difference, in kilovolts, between the sparkover voltage U given by Figure 4 and the measured value corrected to standard atmospheric conditions

S = measured rate of rise of voltage, in kilovolts per nanosecond

If the measured sparkover voltage is lower than that given by Figure 4 the response time is positive; if it is higher, the response time is negative.

In order to achieve the greatest accuracy with this method, the following procedure is recommended:

a) The sphere-gap should initially be set to a spacing of 70 to 75 mm and the impulse generator adjusted to produce across it negative impulses which rise as linearly as possible. The critical part of the recorded voltage rise is the last 40% before the sparkover of the gap (as in Figure 5a, page 69) unless this portion is all above 160 kV. In this latter case, the critical part extends down to 160 kV as in Figure 5b (the approximate value of the 50% sparkover voltage of the gap when set to a spacing of 60 mm).

b) Three impulses should be recorded with the gap set at this larger spacing without any change in the generator settings or controls. The rate of rise is determined for each of the oscillograms and the mean of the three rates is used as S in equation 21a. The rate of rise is the slope of the best fit straight line for the critical part of the voltage rise described in item *a)* above.

c) The gap is then set to the 60 mm value. Three more oscillograms are recorded without any change in the generator settings or controls. The mean of the three recorded sparkover voltages is corrected to standard atmospheric conditions and ΔU determined using Figure 4, page 68, in conjunction with the previously determined value of S. The response time is then calculated using the equation 21a.

d) The procedure is repeated with two other appreciably different rates of rise of voltage to provide three determinations of T.

e) The average of the three response times obtained is the response time of the system and the spread of the three values is indicative of the accuracy of the determination.

Note. – For the use of the method described above it is important that the following requirements are fulfilled:

    a) The gap setting, the irradiation of the gap, and the correction for the atmospheric conditions must be properly done.

    b) The scale factor applicable to the measuring system must be accurately known. The error in the response time determination will be equal to the percentage error in the scale factor multiplied by the time to sparkover.

    c) It must be possible to determine the steepness of the applied voltage from the output of the measuring system, i.e. the applied voltage must be linearly rising for a sufficiently long time to enable the output voltage to follow the input voltage.

    In practice, the sphere-gap method is not usually applicable to large measuring systems since they do not comply with Item *c)* above.

21.2 *Determination of the partial response time T_α or T'_α*

To determine the partial response time T_α or T'_α the same gap as above is used but the setting is no longer critical. To obtain the steepest voltage collapse and to reduce the influence of the impulse generator, it is recommended that a resistor of the order of 10 kΩ be inserted in the lead from the impulse generator to the sphere-gap, at the gap end of the lead. Also, it is desirable that the voltage across the gap has essentially zero rate of rise at the time that the gap sparks over. This can be achieved by chopping an impulse at or near the peak. The resulting record of the voltage collapse can be treated as a step response for the determination of T_α or T'_α. The value obtained will be somewhat larger than that obtained by the unit step method, but it is sufficiently accurate for most purposes.

21.3 *Determination of the response time T_t of the measuring system without high-voltage lead*

The response time T_t is calculated from the value of T determined above in the same manner as described in Sub-clause 20.4.

21.4 *Determination of the resonant frequency range*

The resonant frequency range is determined in the same manner as described in Sub-clause 20.5 using the gap as a step generator as in Sub-clause 21.2.

22. Relation of response parameters to measuring errors

There are three response parameters: response time T, partial response time T_a and initial distortion time T_o, which can cause errors in the measurement of amplitude and time parameters of impulse voltages.

22.1 *Errors caused by response time T*

The response time T affects the measurement of the time parameters and the amplitude of front-chopped impulses.

According to the definition of the response time given in IEC Publication 60–3, the response of the system to a ramp, after a certain time, can be regarded as following the ramp with a delay T, equal to the response time. At the moment of chopping, the difference δ between the applied and measured voltage then becomes:

$$\delta = S \cdot T \qquad \text{Equation 22a}$$

where:
S = steepness of ramp

It can also be shown, as explained in Appendix B, that the same relation can be derived considering the response time determined from the unit step response.

Equation 22a is approximately valid under the following conditions:

− the output voltage form is linear and is parallel to the input voltage form divided by the scale factor;
− a virtual zero point of the response is defined according to Sub-clause 20.1; this point also is considered as the starting point for any voltage to be measured;
− a measure of the response time is used as defined in Sub-clause 20.2;
− the initial distortion time T_o, as defined in Sub-clause 20.3, is sufficiently small.

More general relationships are illustrated in Figure 6a, page 70, for a linearly rising front chopped impulse, in Figure 6b for a non-linearly rising front chopped impulse and in Figure 6c for a full impulse. Figure 6d illustrates a case where a distortion occurs before the peak value is reached. This may be an effect of the initial distortion of the response. It also illustrates how the instant of the measured peak value does not coincide with the moment the chopping occurred which may result in a different error from one given by equation 22a. However, this phenomenon usually can be neglected and, for front chopped impulses, the measuring error δ, defined as the difference between the peak value of the applied voltage and the measured one, becomes approximately:

$$\delta \simeq S_L \cdot T \qquad \text{Equation 22b}$$

where:
S_L = steepness of the applied voltage prior to chopping

Similarly, the error δ_t in the measured time to chopping for a linearly rising applied voltage becomes:

$$\delta_t \simeq T \qquad \text{Equation 22c}$$

For other types of applied voltage, no simple rules can be given.

The error in the measurement of the peak value of full impulses cannot be determined according to the formula since the steepness is zero at the peak. In fact, an amplitude error occurs but the error becomes much less than the one when the impulse is chopped on the front.

The delay, as indicated in Figure 6c, page 70, also gives an error in the measurement of the time parameters of the full impulse. The greater error usually occurs in the measurement of the front time.

The errors in peak value and in time parameters can be evaluated by applying Duhamel's theorem to the response oscillogram and the assumed form of the applied voltage.

22.2 Errors caused by partial response time T_α

The impulse to be measured may have superimposed oscillations. The accuracy with which these are recorded is governed by the steepness of the step response of the measuring system.

IEC Publication 60-2, High-voltage Test Techniques, Part 2: Test Procedures, requires that the amplitude of these oscillations does not exceed 5% of the measured impulse peak value. To comply with this requirement it is necessary to ensure that the system reproduces these oscillations correctly.

The ratio α of the actual to the measured amplitude of these oscillations is given approximately by:

$$\alpha \simeq \sqrt{1+(2\pi f T_\alpha)^2}$$

Equation 22d

where:

f = frequency of oscillation

22.3 Errors caused by initial distortion time T_0

The initial distortion time T_0 can cause additional errors in the measurement of front chopped impulses. No guidance is given concerning corrections for these errors but they can be made negligible by restricting the magnitude of T_0 (see Sub-clause 23.1). If T_0 does not meet the requirements of Sub-clause 23.1, the measuring system preferably should be modified.

23. Criteria relating to corrections

Measurements of the basic impulse shape and peak value can be sufficiently accurate providing they meet the conditions outlined in Sub-clause 23.1.

In certain cases corrections may be made as described in Sub-clause 23.2. Procedures applicable when oscillations exceed permitted levels are mentioned in Sub-clause 23.3 and further described in Appendix C.

23.1 Conditions for measurements to be sufficiently accurate without corrections

a) The response time T must be within the limits specified in Sub-clause 8.2.2 of IEC Publication 60-3.

b) The partial response time T_α and the highest recorded frequency f should meet the following requirements:

$$T_\alpha \leq \frac{2}{\pi f_{max}}$$

Equation 23a

$$f \leq \frac{1}{4\pi T_\alpha}$$

Equation 23b

where:

f_{max} = maximum frequency of oscillations which may reasonably occur in the circuit (see IEC Publication 60-3)

These conditions are explained as follows. In IEC Publication 60–2, the amplitude of oscillations on the peak of an impulse voltage is restricted to 5%. To be discernible, the amplitude on the oscillogram should not be less than about 1%. This applies also to the highest possible frequency, f_{max}. Consequently, it must be required that $\alpha \leqslant 5$ where α is defined according to equation 22d. This leads to the conditions expressed by equation 23a.

If no correction should be necessary, the value of α, at the recorded frequency, should not deviate too much from unity. This gives the condition expressed by equation 23b. Note that in the above equations 23a and 23b, only the value of T_a should be used and not T'_a.

c) The initial distortion time T_o should meet the condition:

$$T_o \leqslant 0.005 \, T_c \qquad \qquad \text{Equation 23c}$$

where:
T_c = time to chopping defined in IEC Publication 60-2

If $T_o > 0.005 \, T_c$, the measuring system should preferably be modified. This is explained as follows. For the determination of the response time of a measuring system, the initial part of the step response is ignored and the response is assumed to start at the point 0' of Figure 7 a, page 71. This assumption means that the time interval 0–0' is regarded as a non-distorting delay, an assumption which is acceptable when dealing with full impulses.

The situation is different however, when dealing with front chopped impulses. If such an impulse is sharply chopped, the chopping can be considered as the addition to the unchopped impulse of a negative step and a negative ramp the former having the same amplitude and the latter the same rate of rise as the unchopped impulse at the moment of chopping. The negative ramp cancels the original rate of rise and the negative step produces the sharp drop in voltage. The behaviour of the measuring system at and following the instant of chopping is therefore determined by the initial portion of the response to these two impulses and primarily by its initial response to a negative step.

If the step response has the shape shown in Figure 7a, a considerable distortion may take place around the peak of the impulse voltage as shown in Figure 7b. The type of distortion depends on the original rate of voltage collapse and of the shape of the step response during the interval 0–0'. Caution should be exercised in the evaluation of such oscillograms. If a correction has to be applied using the response time as defined in this application guide, the highest peak should be considered as the measured value.

23.2 *Conditions for correcting measurements and limits of application of the corrections*

a) Correction of the peak value of a front-chopped impulse is based on the response time T. In the case of impulses chopped on the front after relatively short times, the measuring system may not fulfil the requirements of IEC Publication 60-3. For such cases, and with agreement between the parties involved, an approximate correction of the measured peak value may be made according to:

$$U_{corr} = U_{meas} + S_L \cdot T \qquad \qquad \text{Equation 23d}$$

where:
U_{meas} = measured peak value
U_{corr} = corrected peak value
S_L = slope of the measured impulse prior to the chopping

When corrections for response time are to be made, a test measurement should be made using two different lead lengths for the measuring system. The shorter one should be the length which it is desired to use for the measurement and the longer one should preferably be long enough to bring the response time to within the required limits, or at least long

enough to ensure that the two versions of the measuring system have appreciably different response times. Each of the measurements should then be corrected for the appropriate response time and if the corrected values agree within say 2% or 3% and the correction does not exceed 20%, it can generally be assumed that the method of making the correction is valid.

The only time parameter measurements which can normally be corrected are those in which the two points defining the parameter are located on a portion of the impulse which has a constant slope. This generally means that only measurements of T_r can safely be corrected. T_r is the rise time for a linearly rising front chopped impulse (see IEC Publication 60-2). The correction is made by adding the response time of the system algebraically to the measured value of the time parameter. When such corrections are made, their validity should be checked in the same manner as for corrections to amplitude measurements.

In all cases where measured values are corrected, it is important that every precaution be taken to ensure that the correction is accurate and justified. Even then, the uncorrected results should be reported together with the corrected ones.

b) If the criteria given in equations 23a and 23b are not met, the true amplitude of the oscillations is then obtained by multiplying the recorded amplitude of the oscillation by α, where α is given by equation 23e, except in cases b)1) and b)2) below.

$$\alpha = \sqrt{1 + (2\pi f T_n)^2} \qquad \qquad \text{Equation 23e}$$

where:

f = frequency of the oscillations

1) When the response has a steep initial portion which only extends to a level $k < 1$, and from this level on, the response rises much more slowly (see Figure 8, page 71), a partial response time T'_α is determined. This is the area enclosed by the unit step and the steep portion of the step response extended to unit amplitude.

   If $k > 0.4$

$$\alpha = \frac{1}{k} \sqrt{1 + (2\pi f T_n)^2} \qquad \qquad \text{Equation 23f}$$

   If $k \leqslant 0.4$, equation 23e is used with T_α.

2) In the case of measuring systems with significant resonance, α is taken as unity for frequencies below and within the resonant frequency range. For frequencies above that range, equation 23e should be used.

   Note. – Resonance increases the amplitude of the oscillations. Thus, an application of rule b)2) above will give values on the safe side.

   The corrected amplitudes are compared with the limits given in IEC Publication 60-2, in which oscillations with frequencies above f_{max} are neglected.

   The procedure related to oscillations described in Sub-clauses 23.1b) and 23.2b) is illustrated in the flow diagram of Figure 9, page 73, for non-oscillatory responses and responses with an overshoot, while Figure 10, page 75, applies to responses with a resonant frequency range.

c) There is no recommended correction for the initial distortion time T_0. If the conditions given by equation 23c cannot be met then the measuring system preferably should be modified.

23.3 *Procedures for cases when recorded oscillations exceed permitted level*

While normally oscillations exceeding permitted levels would rule out acceptance of the test voltage, there are conditions under which the test voltage is acceptable. This is the case where the measuring system has a resonant frequency range and within this range it may drastically amplify oscillations present on the test voltage, especially those appearing on the lower portion of the front. If it can be shown by suitable tests that the amplitudes of the oscillations on the test object are negligible, the oscillogram can be considered acceptable provided the presence of the oscillations does not prevent an accurate evaluation of the shape and amplitude of the impulse.

For example, if the impulse is chopped at or near the peak, the recorded oscillations must have died out before this point is reached.

A procedure to determine if the oscillations recorded on the test voltage oscillogram are present on the voltage across the test object is described in Appendix C.

24. Evaluation of a measuring system by comparison method

Instead of determining the performance of a measuring system by analysing its response characteristic, its suitability for the measurement of a particular type of impulse may be determined by comparing the results obtained with those from an independent approved measuring system. If the comparison is made with impulses of different shapes, conclusions can be drawn concerning the range of shapes for which the system is suitable, but in general it is desirable that the comparison be made with the particular impulse shape to be measured. When making such a test, both systems should be connected simultaneously to ensure that the same impulse is being measured by both. This test may be performed at a relatively low voltage level so that an approved system of much lower rating than that being tested may be used. Note that there is a possibility that there may be coupling between the two systems and precautions should be taken to ensure that this does not occur.

25. Various sources of errors, precautions

25.1 *Divider ratio for long impulse duration*

The determination of the impulse voltage duration for which the scale factor of the measuring system is valid is particularly important in the case of capacitor voltage dividers. For such dividers a shunting resistance across the low voltage capacitor of the divider can cause a change in scale factor with duration of the applied voltage; therefore it has to be ensured that the time constant of the low voltage arm of the divider is sufficiently large compared with the longest duration of impulse voltage to be measured.

The apparent variation of ratio can also produce an error in the determination of the response time of the system, as the reference line cannot be determined accurately.

For resistor dividers, it is necessary to ensure that the temperature rise of the resistors is low enough to prevent any appreciable change in the resistance value during the duration of the impulse.

25.2 *Proximity effects*

Both the voltage ratio and the response time of a voltage divider may be affected by changes in the capacitance to earth. It is important that the determinations of response times and divider ratios be made with the apparatus in a typical working position relative to other objects.

The minimum clearance which must be maintained between a measuring system and other objects which are at either earth or high potential should be determined (see IEC Publication 60-3). One method of doing this is to investigate the effects on the step response when a vertical earth plane for instance, is placed at different distances from the voltage divider. In the case of resistor dividers, when the earth plane is too close, the shape of the step response will be affected because the stray capacitances to earth are augmented. The change in shape might not be readily apparent from a visual inspection of the response so the effect on T_a and T_t should be used as an indication of when the minimum clearance has been reached.

This method is not too reliable for dividers involving capacitors because the stray capacitances to earth may affect the scale factor rather than the response characteristics. For such dividers, the scale factor should be measured or compared with that of some other system while the proximity effect is being investigated. This can be done by making simultaneous measurements with both systems as the earth plane is being moved in towards the divider of the system being investigated.

With a slight variation, the above method can also be used to check the proximity effect of objects at high voltage. In this case, the moveable plane is live instead of being earthed. A method for carrying out this check is illustrated in Figure 11, page 76. Here a transient voltage is applied to the moveable plane during the recording of the step response of the measuring system and the time at which this voltage is applied can be adjusted by changing the length of the lead between the moveable plane and the step generator. Varying the length of this lead can sometimes increase the sensitivity of the detection of proximity effects.

Another variation of the technique may be used to check the effect of having the high voltage lead at different angles relative to the axis of the divider. In this case the moveable plane is removed from the circuit and the step response is measured for different angles of the high voltage lead relative to the axis of the divider.

25.3 *Corona effects, precautions*

Corona on the high-voltage lead may change the response time of a measuring system and corona from metalwork at intermediate points on a voltage divider may be responsible for measuring errors. In most cases, the use of connections of large diameter and of suitable screening rings will reduce these effects, providing they are corona-free. If not corona-free, they may affect the response time and the measuring errors.

25.4 *Disturbance level check*

Spurious indications on instruments or oscilloscopes may occur due to large currents circulating in the earthing system (especially in the sheaths of measuring cables), or to the influence of stray fields on either the measuring circuit or the instrument itself.

One method for investigating the disturbance level caused by currents in the sheath of a measuring cable is to short-circuit the input end of the cable, leaving the sheath connected to the earth terminal of the voltage divider as in an actual test and without changing any other connections in the circuit. If an impulse of about 60–100% of the normal test value is generated in the

test circuit, the deflection on the instrument should be negligible, say 1–2%, for the system to be considered free of disturbance. If an appreciable deflection is obtained, the test can be repeated with the cable matched at its input end instead of being shorted. If this eliminates the deflection then the system can generally be considered satisfactory. It should be pointed out that neither of these approaches gives a true indication of the disturbance level and the disturbance recorded may be exaggerated. However, if the disturbance is significant as shown by these tests, efforts should be made to eliminate it.

To reduce the disturbance level, loops in the layout of the earthing system should be eliminated or reduced to the smallest practicable dimensions. It is also possible in some cases to effect an improvement by using double shielding on the measuring cable and by improving the shielding and isolation of the measuring instrument.

To reduce magnetic coupling, measuring cables should whenever possible be located away from conductors carrying heavy currents.

Flashover phenomena can create measuring errors or oscillations.

In a system whose high frequency response appreciably exceeds its response in the low frequency range, two phenomena may occur:

a) disruptive discharge of the test object may result in overstressing the measuring equipment;

b) extensive partial discharges may produce measuring errors.

These phenomena are usually associated with the presence of stray inductances in underdamped capacitive circuits. Heavy overshoot on an experimental step response is often indicative of this condition.

Excessive voltage drops may occur even on short lengths of ground conductor. These may give rise to measuring errors or may cause spurious oscillations due to sparking.

In the analysis of experimental step response, inaccuracy in determining the level of the unit step can be a major source of error in determining the various response times.

SECTION FIVE – MEASUREMENT OF IMPULSE CURRENTS

26. General

Measuring systems for impulse currents must be capable of handling very high currents – of the order of tens or even hundreds of thousands of amperes. Because of the very rapid rates of change of current involved, the inductance of the impulse-current circuit must be kept low and careful attention paid to the design of the components to ensure this. It is also important that the insertion of the measuring system into the test circuit should not introduce unnecessary impedances.

27. Commonly used measuring systems

The following are typical systems used for measuring impulse currents:

a) shunt with oscilloscope or peak reading instrument;

b) current transformer with oscilloscope or peak reading instrument.

27.1 Measuring system components

Many of the components of an impulse current measuring system are the same as those used in voltage measuring systems and they should meet the same requirements as outlined in the appropriate parts of Clause 16. The following components are specifically for current measuring systems.

a) *Shunt*

The most commonly used form of shunt is that having a tubular construction. Figure 12, page 77, shows the construction features of some examples of this type of shunt. The resistance material used should be non-magnetic.

b) *Current transformers*

Specialised wide-band current transformers can be used for the measurement of short duration impulses. They are advantageous over shunts in so far as they permit isolation from earth and hence can be arbitrarily located in the current circuit. No guidance is given here on the design features of such components.

27.2 Step response of current measuring systems

The response time of a current measuring system must be determined experimentally; however, the method outlined below for calculating the response time of tubular shunts may prove useful in design.

a) *Response time of tubular shunts*

Tubular resistance shunts usually have an aperiodic type of step response and if the actual zero is used the response time is given approximately by:

$$T = \frac{\mu_o}{6} \cdot \frac{d^2}{\varrho}$$

where:

μ_o = permeability of free space, $4\pi \cdot 10^{-7}$ H/m
T = response time, in seconds
d = wall thickness of resistance tube, in metres
ϱ = resistivity of the tube material, in ohms-metres

However, due to the use of the virtual zero 0', the response time is determined more accurately from:

$$T = \frac{\mu_o}{8} \cdot \frac{d^2}{\varrho}$$

Note. – The response of tubular shunts may be improved by including a compensating network in the part of the shunt which provides the output voltage signal. Such a compensating network may be magnetically coupled with the current carrying part of the shunt.

b) *Experimental determination of the step response*

To determine the response time of a current measuring system, a step of current is applied to the system and the resulting response is treated in the same manner as outlined in Clause 19 for impulse voltage systems. However, the response time obtained by integrating the experimental step response is the true response time of the system and needs no correction, since there are no long leads associated with its determination.

The basic difference between the methods of obtaining the step response for current measuring systems and for voltage measuring systems is that the latter are obtained using a zero impedance

source whereas the current responses should be obtained with an infinite impedance source. This is not practical, but it is generally satisfactory if the impedance of the step generator is very large compared with the impedance of the current measuring system.

A practical form of step generator is a charged cable or transmission line which is switched onto the measuring system as illustrated in Figure 13, page 77. When the switch is closed, a current step with an amplitude equal to the quotient of the charging voltage divided by the cable characteristic impedance, will be applied to the measuring system. The cable must be long enough to ensure that the response of the measuring system has settled before a reflection from the opposite end of the cable arrives at the switch. This method is similar to that for obtaining the step response of a voltage measuring system (see Clause 19), the difference being that here the switch connects a voltage source to the system whereas in the other, the switch generates the step by short-circuiting the input of a charged system. Because of the similarity of the two methods, the same types of switches are used and the same conditions regarding amplification apply.

28. Precautions

In circuits where high current impulses occur, the voltage drops on even short lengths of conductor may be considerable. Precautions are necessary to ensure that these do not result in measuring errors and that the earthing of test circuits is such that damage to the insulation of measuring or recording instruments does not occur.

Stray magnetic fields may also cause measuring errors which can be detected by altering the arrangement of conductors.

In addition, some specific precautions should be taken depending on the use of either shunts or current transformers.

a) *Shunts*

Care should be taken to ensure that the resistance of the shunt does not change appreciably with heating caused by the impulses to be measured. The thermal capacity of the shunt should be sufficient to prevent permanent damage in case of failure of a series impedance such as the test object or a damping resistor.

b) *Current transformers*

They are generally of narrower bandwidth than shunts and are not capable of transferring d.c. components.
The amplitude of the step response of a current transformer decreases with time; and the rate of decrease is determined by the ratio of mutual inductance and burden resistance.

The operating range of current transformers having magnetic cores is limited by core saturation. In order to avoid saturation the maximum charge flowing in any given direction should not exceed the rated ampere-second product of the transformer for a given resistive burden.

SECTION SIX – MEASURING ERRORS

29. Statistical evaluation

In any measurement the actual value obtained differs by a certain amount from the true value. This difference may come from two main causes:

a) The measuring system is not perfect, the recorded value being different from the value to be measured divided by the scale factor. That may be due for example to the effect of the response time, and a corrected value has to be calculated if needed.

b) The characteristics of the measuring system are not known perfectly. Observational and environmental errors may occur at random. If these errors are called e_1, e_2, e_3 ... e_n, and, if all these errors are independent, they are likely to be both positive and negative and the statistical overall error is equal to:

$$E_\cdot = \sqrt{e_1^2 + e_2^2 + e_3^2 + ... + e_n^2}$$

Consequently, the errors may be considered as following a Gaussian distribution defined by a standard deviation σ and with a mean value equal to zero. Under this assumption, the error $E = \pm 2\,\sigma$ has less than 5% probability of being exceeded and, therefore, is referred to as "the maximum error".

APPENDIX A

RESISTOR DIVIDERS

As a first estimate, neglecting a number of factors such as the inductance of the divider and the effect of the low-voltage arm and noting that the real zero 0 is the origin for the response, the response time of a vertical resistive divider without a high-voltage shield electrode and with the bottom at ground level, is given approximately by:

$$T_t \simeq \frac{R\,C}{6}$$

where:
T_t = divider response time in seconds
R = total divider resistance in ohms
C = total divider capacitance to earth in farads (the capacitance can be measured by a conventional capacitance measuring bridge)

However, due to the use of the virtual zero', the response time is determined more accurately from

$$T_t \simeq \frac{R\,C}{8}$$

The capacitance C of a vertical divider can be determined as the capacitance of a vertical conductor if the bottom of the divider is approximately at ground level:

$$C = 2\pi\varepsilon_o \frac{\ell}{\ln \dfrac{\ell}{r\sqrt{3}}}$$

where:
ε_o = dielectric constant of vacuum = $8.85 \cdot 10^{-12}$ F/m
ℓ = length of the divider in metres
r = radius of the divider in metres

APPENDIX B

MATHEMATICAL BASIS FOR RESPONSE TIME T

The response time is defined in terms of the instantaneous measurement error relative to the rate of change of the quantity being measured (see Sub-clause 4.6 in IEC Publication 60-3).

The idealized response time is equal to the algebraic sum of the areas between the unit step response and unit amplitude (see Figure 3, page 67):

$$T = T_\alpha - T_\beta + T_\gamma - \dots$$

This relationship can be derived by analysing the behaviour of a measuring system when it is used to measure a linearly rising voltage of the form: $U = S \cdot t$, S being the steepness. Such a voltage can also be regarded as being the integral of a step of amplitude S:

$$U = S \cdot t = \int_0^t S \, dt = S \int_0^t dt$$

If the measuring system has a normalized step response $g(t)$, its normalized response U_o to the above voltage will then be:

$$U_\text{o} = \int_0^t S g(t) \, dt = S \int_0^t g(t) \, dt$$

and the difference between the input voltage and the recorded voltage at any instant T_x will be:

$$\delta = S \int_0^{T_x} dt - S \int_0^{T_x} g(t) \, dt = S \int_0^{T_x} (1 - g(t)) \, dt$$

Once the time T_x is reached when the input and the output voltages are changing at the same rate, the amplitude error remains constant and from then on:

$$\int_0^{T_x} (1 - g(t)) \, dt \to \int_0^\infty (1 - g(t)) \, dt$$

Thus the difference between the input and recorded voltages is given by:

$$\delta = S \int_0^\infty (1 - g(t)) \, dt$$

From the definition of the response time T, this difference is:

$$\delta = S \cdot T$$

Therefore:

$$T = \int_0^\infty (1 - g(t))\, dt$$

In practice, the integration is performed up to the time when the step response reaches an essentially constant value.

APPENDIX C

PROCEDURE TO DETERMINE IF OSCILLATIONS ARE PRESENT ACROSS THE TEST OBJECT

The following procedure may assist in determining whether oscillations are present across the test object:

a) If the measuring system has no resonant frequency, as for example when the step response is exponential, the measuring system cannot give rise to oscillations. Thus oscillations on the test oscillogram are generated in the impulse generator circuit, including the test object and the front capacitor. If the amplitudes of the oscillations on the test oscillogram, multiplied by the factor α, exceed the limits set forth in IEC Publication 60-2, the generator circuit should be changed.

b) If the measuring system has a resonant frequency range, oscillations on the oscillogram with frequencies above or below this range cannot be created by the measuring system. The only source must be the generator circuit. If the amplitudes of the oscillations on the test oscillogram, multiplied by the factor α exceed the limits above, the generator circuit should be changed.

c) If the measuring system has a resonant frequency range, oscillations with a frequency within this range can be caused either by the measuring system or by the generator circuit. To determine which condition exists; a resistor of a value of 300 Ω to 500 Ω can be inserted between the test object and the input end of the high-voltage conductor to the divider. Two cases can be distinguished, c_1) and c_2).

c_1) The oscillations do not essentially vanish and consequently their origin lies in the generator circuit. If the amplitudes of the oscillations on the original test oscillogram exceed the limits above, the oscillogram cannot be accepted and the generator circuit should be changed.

c_2) The oscillations do essentially vanish, consequently they orginate in the measuring system. The oscillations of the H. V. measuring system will cause oscillations in the circuit formed by the test object, the front capacitor and the high-voltage conductor.
The frequencies of the oscillations are inversely proportional to the square root of the capacitances of the divider and of the test object plus front capacitor respectively.

Thus:

– if the capacitance of the divider is small compared with that of the test object plus the front capacitor it can be assumed that there will be negligible oscillations on the test object whereas the test oscillogram can exhibit heavy oscillations; therefore the oscillogram may be accepted;

– if the capacitance of the divider is of the same order or larger than that of the test object plus front capacitor, it can be assumed that the oscillations on the test object are at least of the same order as on the divider, therefore the oscillogram cannot be accepted.
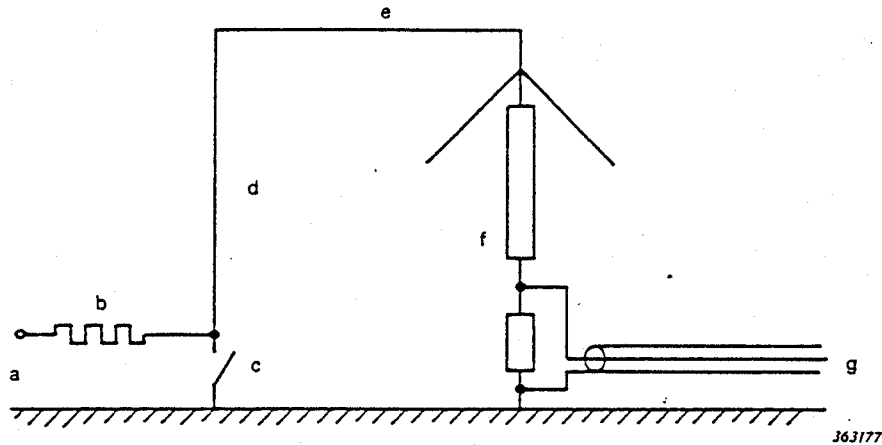
a = source de tension continue ou générateur de choc
b = résistance
c = générateur d'échelon
d = conducteur vertical ajouté, longueur h
e = conducteur à haute tension, longueur l, hauteur h
    au-dessus de la terre
f = diviseur de tension
g = à l'oscillographe

a = to d.c. supply or impulse generator
b = resistor
c = step generator
d = added vertical lead, length h
e = high-voltage lead, length l, height h above ground
f = voltage divider
g = to oscilloscope

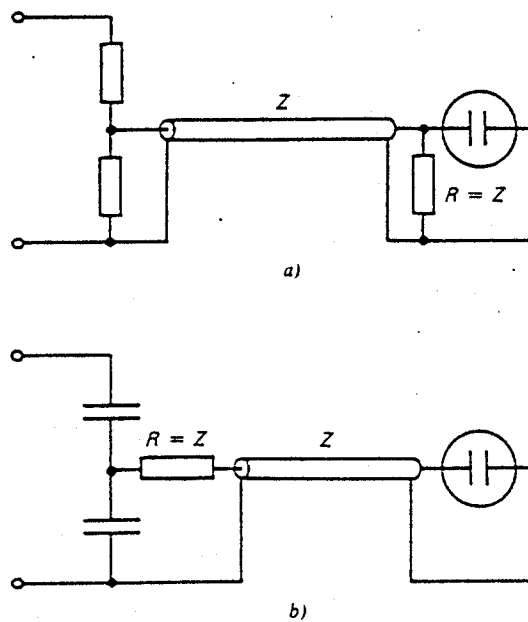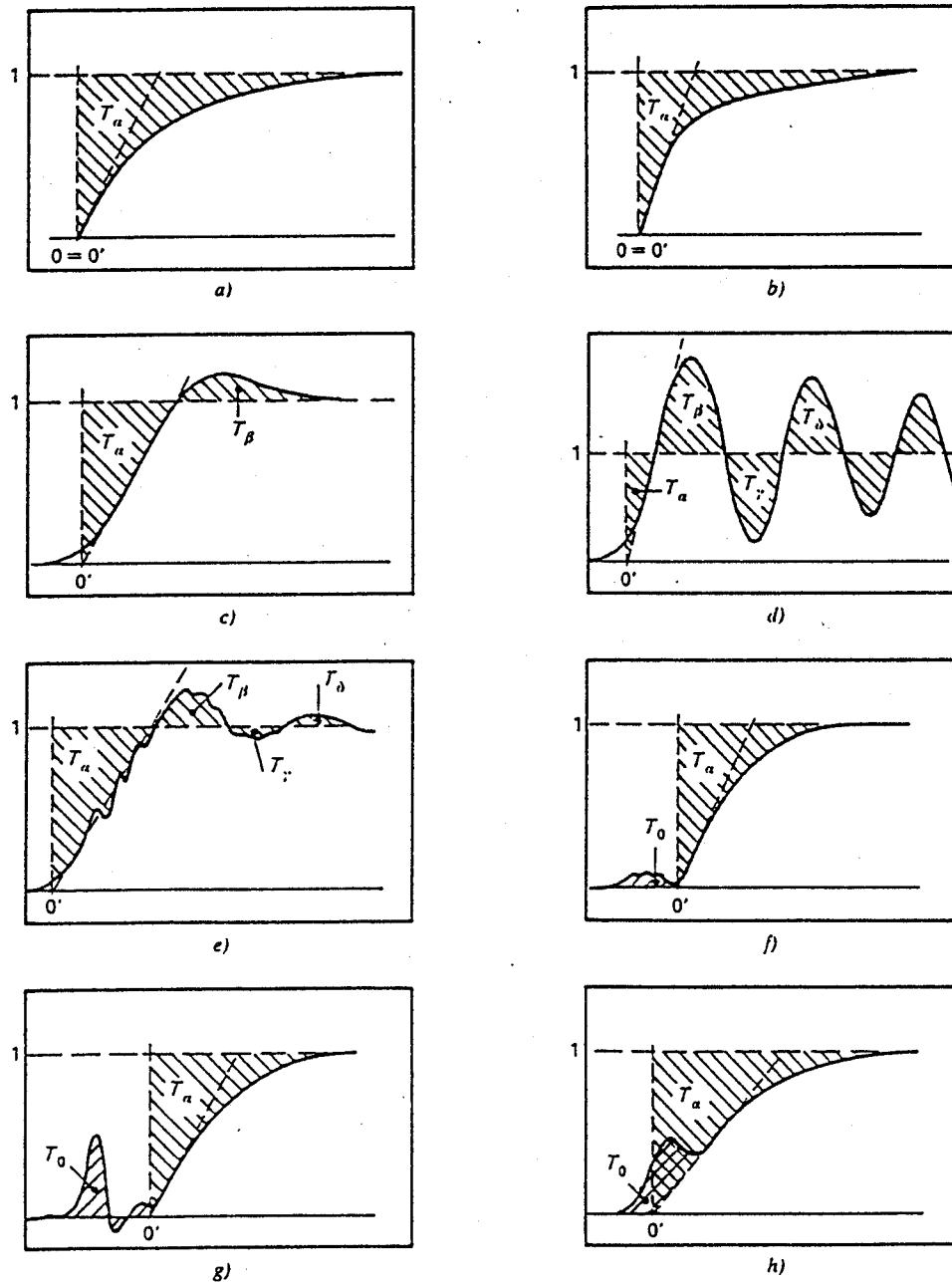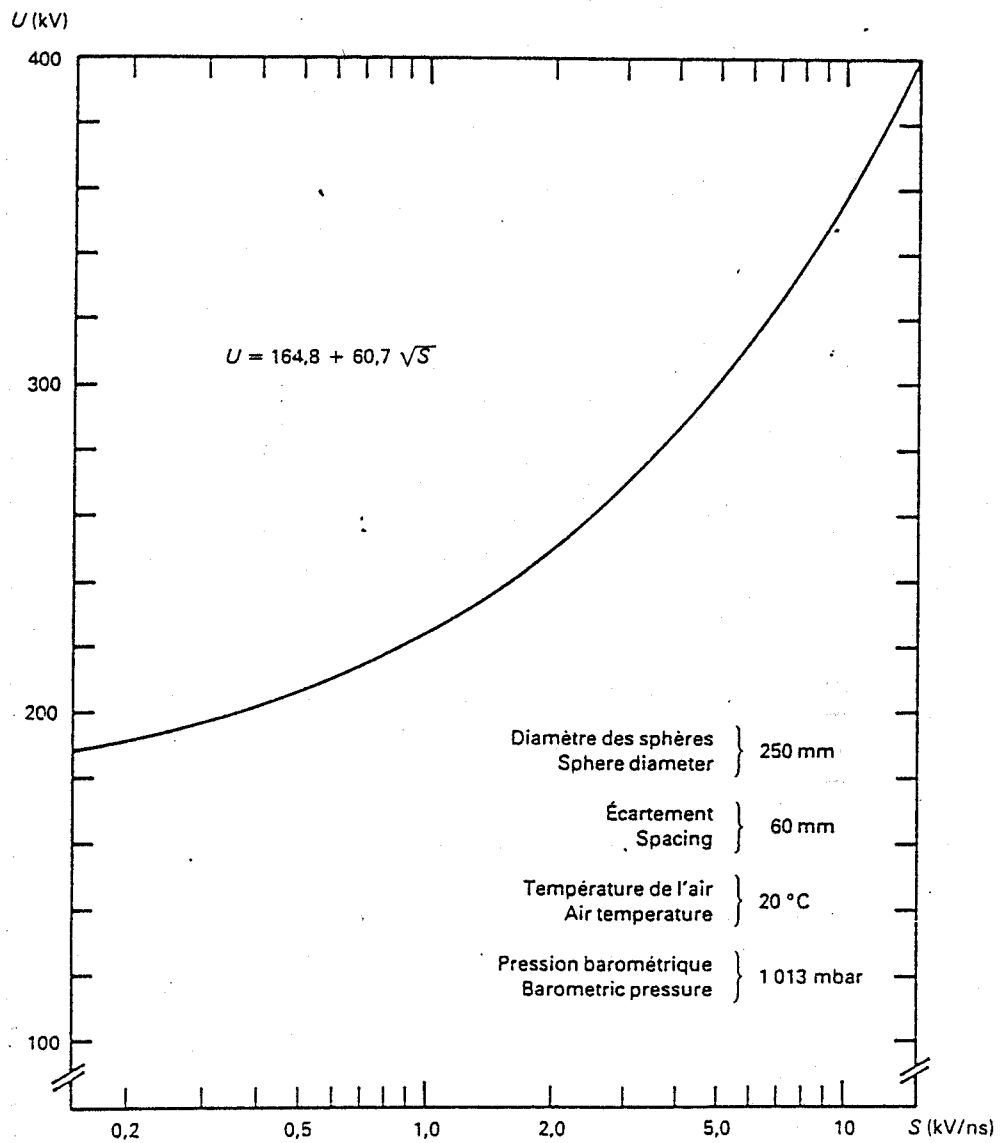FIG. 1. – La méthode de l'échelon unité.
The unit step method.

FIG. 2. – Méthodes d'adaptation des câbles coaxiaux.
Methods of matching coaxial cables.

FIG. 3. — Oscillogrammes typiques obtenus par la méthode à l'échelon.
Typical oscillograms obtained by the step method.

U (kV)

$$U = 164,8 + 60,7 \sqrt{S}$$

| Diamètre des sphères
Sphere diameter | 250 mm |
Écartement Spacing	60 mm
Température de l'air Air temperature	20 °C
Pression barométrique Barometric pressure	1 013 mbar

S (kV/ns)

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FIG. 4. – Tension d'amorçage d'un éclateur à sphères en fonction de la raideur (valable pour des tensions négatives).
Sphere-gap sparkover voltage as a function of steepness (valid for negative voltages).
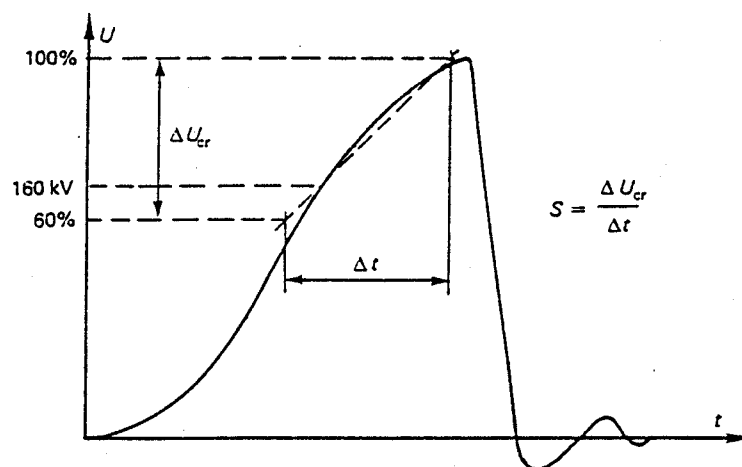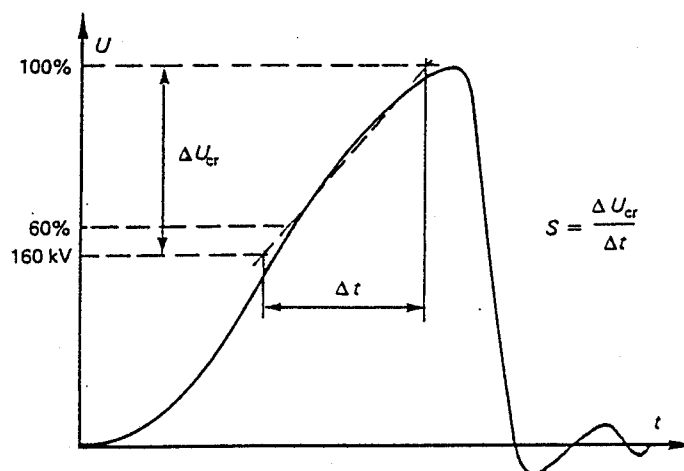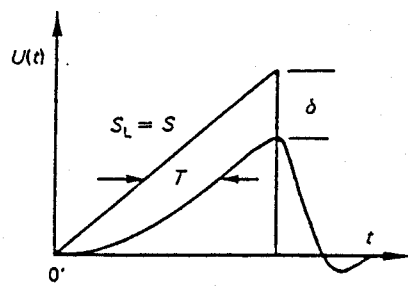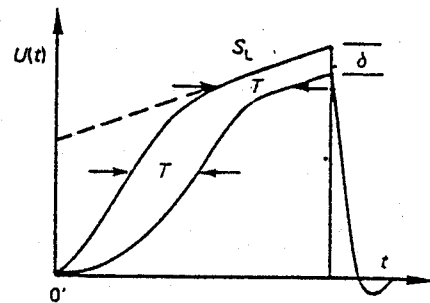
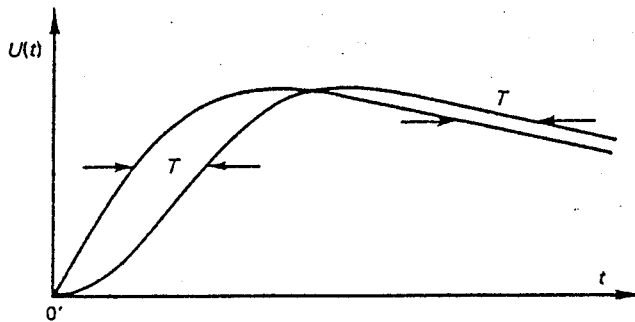FIG. 5 – Détermination de la pente en utilisant la méthode de l'éclateur à sphères.
Determination of steepness when using sphere-gap method.
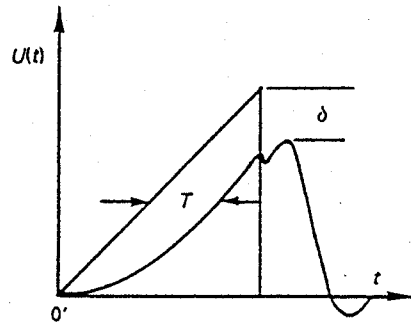
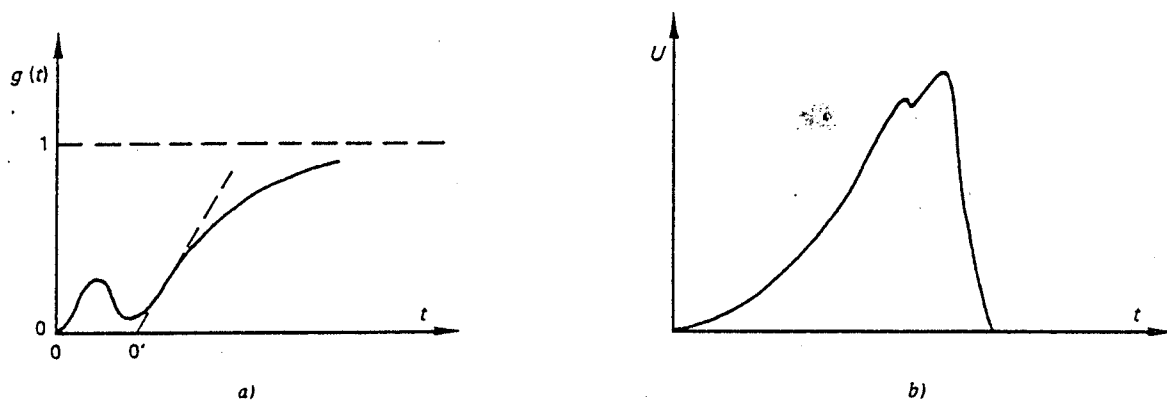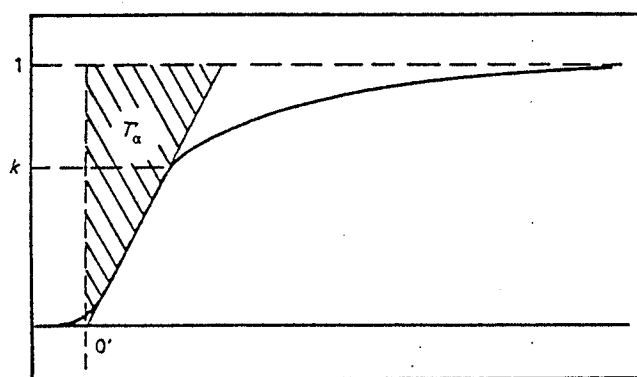FIG. 6. – Temps de réponse et erreurs de mesure dans les mesures réelles.
Response time and measuring errors in practical measurements.
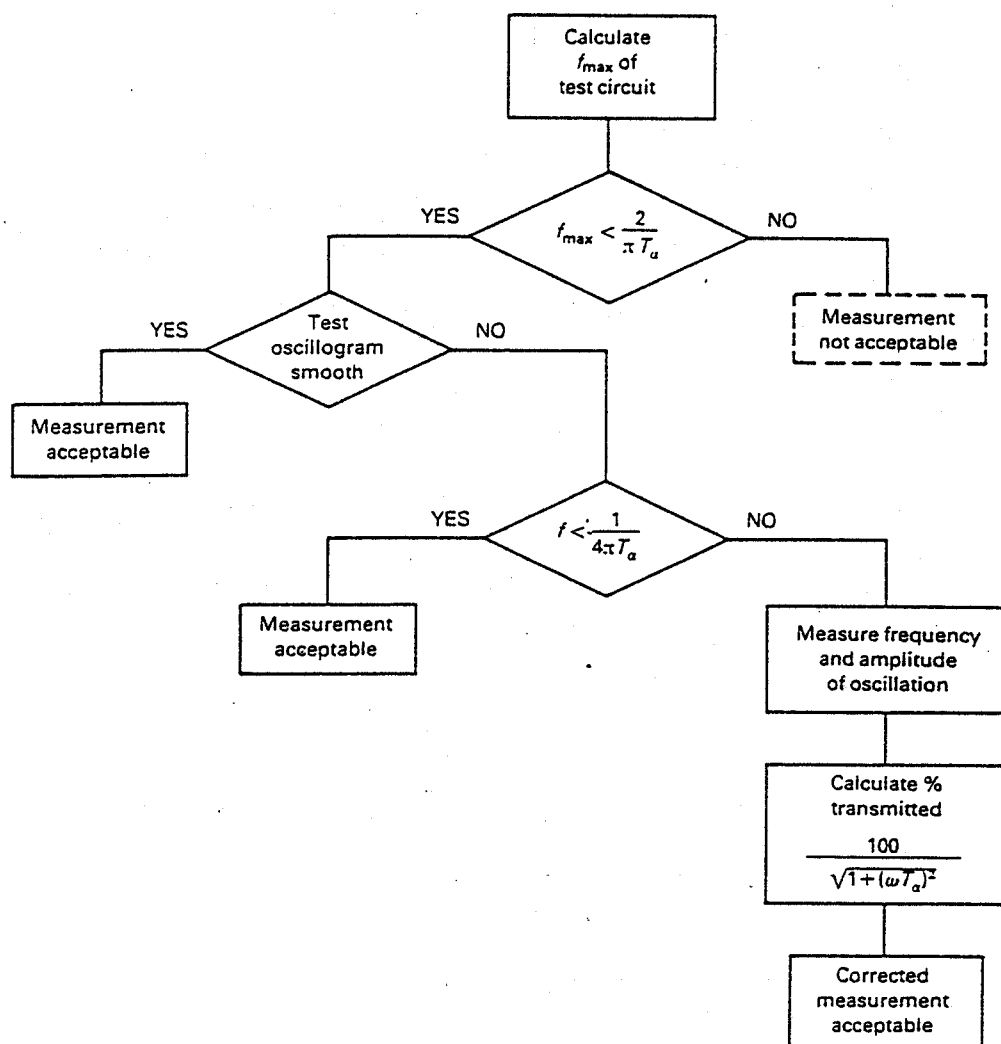
FIG. 7. – Effet de la distorsion initiale sur un choc coupé sur le front.
Effect of initial distortion on front-chopped impulse.

FIG. 8. – Détermination de T'_a pour une réponse ayant une portion initiale raide.
Determination of T'_a for a response with steep initial portion.

FIG. 9 – Flow diagram for evaluating impulse oscillograms – Non-oscillatory step response.

The flowchart contains the following elements:

- Calculate f_{max} of test circuit
- Decision: $f_{max} < \dfrac{2}{\pi T_a}$
  - NO → Measurement not acceptable
  - YES → Test oscillogram smooth
    - YES → Measurement acceptable
    - NO → Decision: $f < \dfrac{1}{4\pi T_a}$
      - YES → Measurement acceptable
      - NO → Measure frequency and amplitude of oscillation → Calculate % transmitted $\dfrac{100}{\sqrt{1+(\omega T_a)^2}}$ → Corrected measurement acceptable

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Notes 1. – For any measurement, the response time requirement must be met.

2. – An acceptable measurement is a prerequisite for determining whether or not the test voltage is acceptable.

3. – Even though a measurement is acceptable the test voltage is not necessarily acceptable.

4. – An acceptable measurement is only valid up to the instant of chopping on chopped oscillograms.

Calculate f_{max} of test circuit

$f_{max} < \dfrac{2}{\pi T_\alpha}$

YES — Test oscillogram smooth — NO

NO — Measurement not acceptable

YES — Measurement acceptable

Measure frequency and amplitude of oscillation

Compare oscillation freq. with f_r*

$f < f_r$ — Measurement acceptable

$f > f_r$

$f \approx f_r$

$f < \dfrac{1}{4\pi T_\alpha}$ — YES — Measurement acceptable — NO

Calculate % transmitted
$$\dfrac{100}{\sqrt{1 + (\omega T_\alpha)^2}}$$

Corrected measurement acceptable

Test voltage proved oscillation free

YES — Test voltage characteristics clear despite oscillation — NO

NO — Assume oscillation transmitted 100%

Measurement acceptable

YES — Draw a smooth curve

Measurement acceptable

Measurement not acceptable

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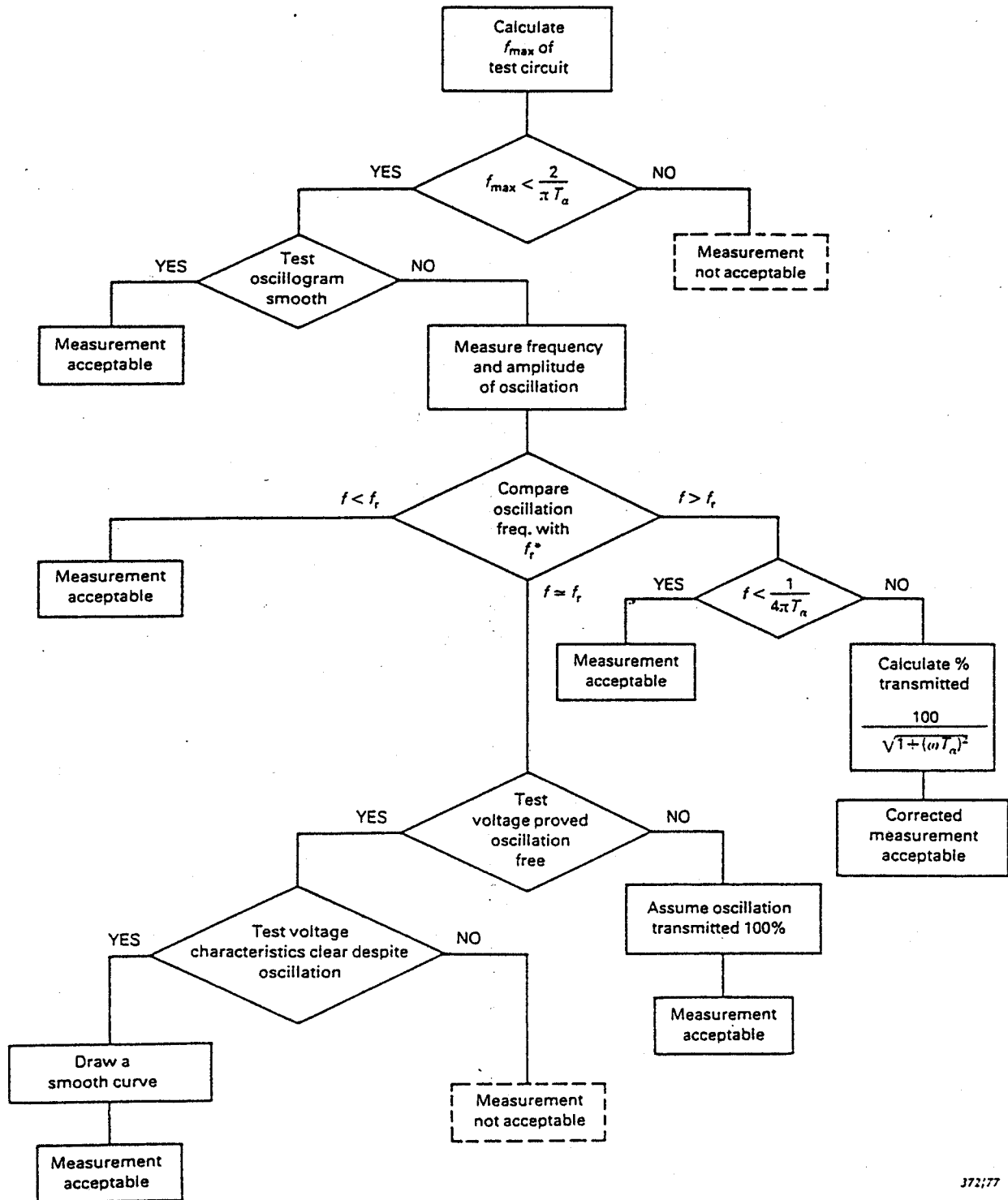* f_r is any frequency within the resonant frequency range

Notes 1. – For any measurement, the response time requirement must be met
2. – An acceptable measurement is a prerequisite for determining whether or not the test voltage is acceptable.
3. – Even though a measurement is acceptable the test voltage is not necessarily acceptable.
4. – An acceptable measurement is only valid up to the instant of chopping on chopped oscillograms.

FIG. 10. – Flow diagram for evaluating impulse oscillograms – Oscillatory step response.
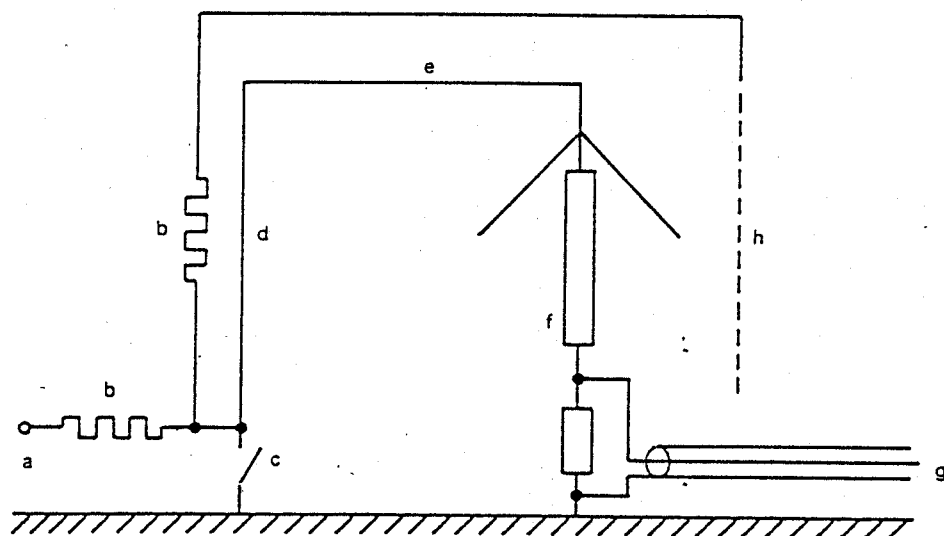
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a = source de tension continue
    ou générateur de chocs

b = résistances

c = générateur d'échelon

d = conducteur vertical ajouté, longueur *h*

e = conducteur à haute tension, longueur *l*,
    hauteur *h*, au-dessus de la terre

f = diviseur de tension

g = à l'oscillographe

h = écran métallique

a = to d.c. supply
    or impulse generator

b = resistors

c = step generator
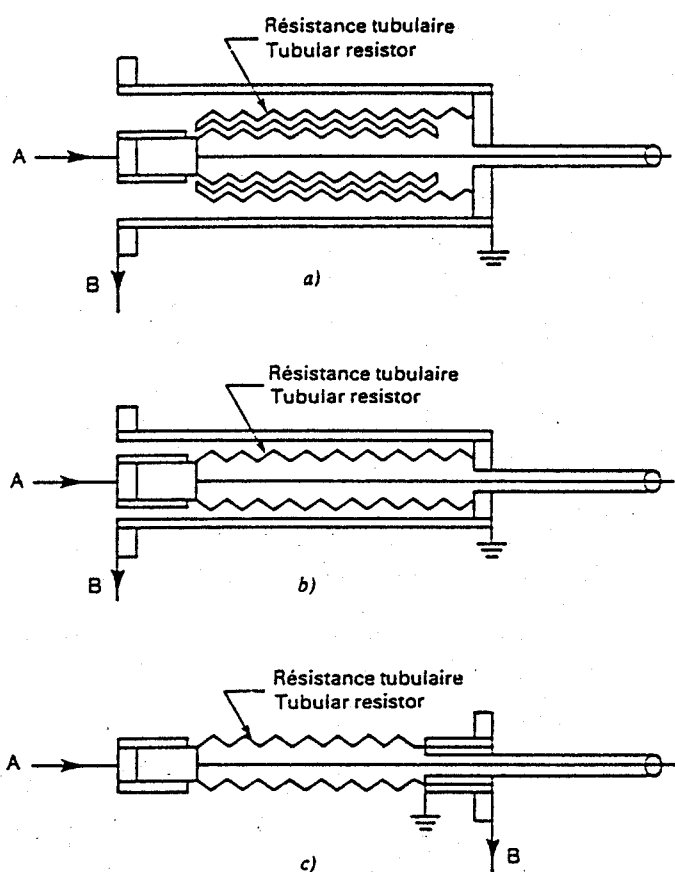
d = added vertical lead, length *h*

e = high voltage lead, length *l*, height *h*,
    above ground

f = voltage divider

g = to oscilloscope

h = metallic screen

FIG. 11. – Vérification des effets de proximité.
Check of the proximity effects.

a) = shunt à tube multiple et à retour coaxial

b) = shunt à retour coaxial

c) = shunt à retour non coaxial

Le circuit du générateur de choc est connecté entre les points A et B

a) = multiple tube, coaxial return

b) = coaxial return

c) = non coaxial return

The impulse current flows from point A to point B

FIG. 12. – Shunts tubulaires pour la mesure des courants de choc.
Tubular shunts for impulse current measurements.
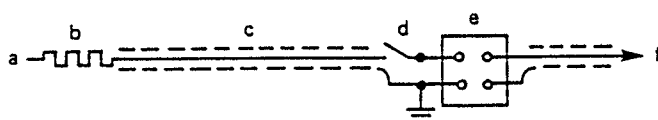
a = alimentation en courant continu

b = résistance de découplage

c = câble coaxial

d = générateur d'échelon

e = shunt

f = vers l'oscillographe

a = d.c. supply

b = isolating resistor

c = coaxial cable

d = step generator

e = shunt

f = to oscilloscope

FIG. 13 – Détermination de la réponse à l'échelon des circuits de mesure de courant de choc.
Determination of step response of impulse current measuring systems.

Autres publications de la CEI préparées
par le Comité d'Etudes n° 42

Other IEC publications prepared
by Technical Committee No. 42

52 (1960)	Recommandations pour la mesure des tensions au moyen d'éclateurs à sphères (une sphère à la terre).
60: – Techniques des essais à haute tension.	
60-1 (1973)	1^{re} partie: Définitions et prescriptions générales relatives aux essais.
60-2 (1973)	2e partie: Modalités d'essais.
60-3 (1976)	3e partie: Dispositifs de mesure.
270 (1968)	Mesure des décharges partielles.

52 (1960)   Recommandations pour la mesure des tensions au moyen d'éclateurs à sphères (une sphère à la terre).
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60-3 (1976)   3e partie: Dispositifs de mesure.
270 (1968)   Mesure des décharges partielles.

52 (1960)   Recommendations for voltage measurement by means of sphere-gaps (one sphere earthed).
60: – High-voltage test techniques.
60-1 (1973)   Part 1. General definitions and test requirements.
60-2 (1973)   Part 2. Test procedures.
60-3 (1976)   Part 3. Measuring devices.
270 (1968)   Partial discharge measurements.